VIOLENT STAR AND STAR CLUSTER FORMATION IN NEARBY AND DISTANT GALAXIES

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I present recent observations and analyses of star cluster formation in a wide variety of environments – from young star clusters and super star clusters in normal actively star-forming spirals and irregulars to starbursting dwarfs and spiral-spiral mergers. Star cluster formation in interacting galaxies can be restricted to central starburst region, extend over the entire body of the merger, or even all along extended tidal structures. I address methods and results for the determination of star cluster ages, metallicities, masses, and sizes and discuss the nature, possible lifetimes and future signatures of these star cluster populations, as well as the relative importance of field star formation vs. star cluster formation.

Keywords: Stars: formation, Galaxies: evolution, formation, interactions, ISM, starburst, star clusters, Globular Clusters: general, Open Clusters and Associations: general

1 Introduction

I briefly and selectively review some aspects of **S**tar **F**ormation (**SF**) in the context of a comparison between normal SF and violent SF in starbursting and interacting galaxies and between SF in the local universe and at high redshift. **S**tar **C**luster (**SC**) formation is an important mode of SF, in particular during violent SF episodes. SCs – as far as they survive – are much better tracers of (violent) SF in galaxies than integrated light because they can be studied one by one. The age and metallicity distributions of SC and **G**lobular **C**luster (**GC**) systems hold unique clues about the formation histories of their parent galaxies over cosmological timescales.

In Sect. 2. I will review some aspects of normal vs. violent SF, in Sect. 3. I sketch the present state of our knowledge about SC formation, both in terms of observational evidence and theoretical concepts, and in Sect. 4. I discuss the relation between SC formation and field star formation and in Sect. 5 I summarise and present an embarrassingly long list of open issues.

2 Star Formation : normal and violent

Star **F**ormation **R**ates (**SFR**s) in nearby normal and starburst galaxies are conventionally derived from their H_α-luminosities via

$$\mathrm{SFR}\ [\mathrm{M}_\odot/\mathrm{yr}] \ = \ \mathrm{L}(\mathrm{H}_\alpha\ /\ 1.26 \cdot 10^{41})\ [\mathrm{erg/s}].$$

This assumes a Salpeter IMF from $0.1 - 100\ \mathrm{M}_\odot$ and approximately solar metallicity (cf. e.g. Kennicutt 1998). As we have shown in Weilbacher & Fritze – v. Alvensleben (2001) using our GALEV evolutionary synthesis models, this relation is only valid as long as SFRs do not fluctuate on timescales $\leq 10^7$ yr. In the case of individual SFing regions or for starbursting dwarf galaxies which have SF fluctuations on timescales of 10^5 to 10^6 yr, the SFRs estimated from their H_α-luminosities can be wrong by as much as a factor of ~ 100, because changes in H_α emission lag behind changes in the SFR by about the lifetime of the most massive stars. Moreover, because low metallicity stellar populations are brighter and have much stronger ionising fluxes than solar metallicity ones, the above relation becomes metallicity dependent. For $\mathrm{Z} = 1/20 \cdot \mathrm{Z}_\odot$, e.g., SFRs derived from the above relation are overestimated by a factor ≤ 3 for continuous SF and by a factor ≥ 3 for starbursts.

Tight correlations are observed between H_α-derived SFRs and UV-, mid-IR-, FIR-, and radio-luminosities, that then, in turn, can also be used to estimate galaxy SFRs.

For distant galaxies, SFRs are often derived from their [OII]3727-luminosities via

$$\mathrm{SFR}\ [\mathrm{M}_\odot/\mathrm{yr}] \ = \ \mathrm{L}([\mathrm{OII}]\ /\ 7.14 \cdot 10^{40})\ [\mathrm{erg/s}].$$

The metallicity dependence of the [OII]3727–line is twofold. [OII] fluxes depend on the oxyen abundance and, hence, increase with increasing metallicity of the ionised gas. They also depend on the strength of the ionising flux that decreases with increasing metallicity. The combination of both effects accounts for a factor ~ 2 change from high to low metallicity in the transformation factor between L([OII]) and SFR (see Weilbacher & Fritze – v. Alvensleben 2001), resulting in an overestimate of SFRs based on [OII] in low metallicity galaxies when using the conventional relation derived for local near-solar metallicity galaxies (cf. Kewley *et al.* 2004, Bicker & Fritze – v. Alvensleben *submitted*).

SFRs are of order $1 - 3\ \mathrm{M}_\odot/\mathrm{yr}$ for spiral galaxies with masses around $10^{10}\ \mathrm{M}_\odot$ and of order $0.01 - 3\ \mathrm{M}_\odot/\mathrm{yr}$ for irregular and dwarf irregular galaxies with masses in the range 10^6 to $10^9\ \mathrm{M}_\odot$. Starbursts in isolated dwarf galaxies have SFRs of order $0.1 - 10\ \mathrm{M}_\odot/\mathrm{yr}$.

Bursts strengths – defined as the relative increase of the stellar mass during a burst $\mathrm{b} := \Delta \mathrm{S}_{\mathrm{burst}}/\mathrm{S}$ can reasonably be derived for young post-starbursts only. For a sample of BCDGs with optical and NIR photometry burst strengths have been shown by Krüger, Fritze – v. Alvensleben & Loose (1995) to range from $\mathrm{b} = 0.001$ to $\mathrm{b} = 0.05$, and to decrease with increasing total mass, including their important HI masses, in agreement with expectations from stochastic self-propagating SF scenarios (cf. Fig.1).

Massive gas-rich interacting galaxies feature high and sometimes very high SFRs of order 50, 100, up to $1000\ \mathrm{M}_\odot/\mathrm{yr}$ and more for **L**uminous and **U**ltraluminous **IR G**alaxies (**LIRG**s and **ULIRG**s) and their higher redshift counterparts, the SCUBA galaxies, in their global or nuclear starbursts which typically last for a few 10^8 yr. Evolutionary synthesis modelling of post-starbursts in local massive gas-rich spiral – spiral merger remnants have shown that these systems can also have tremendous bursts strengths that increased their stellar masses by $10 - 50\%$. In the case of NGC 7252, the very strong Balmer absorption lines can only be reproduced with a burst that increased the stellar mass by at least 30 and possibly up to 50% (Fritze – v. Alvensleben & Gerhard 1994a, b). Starbursts in massive interacting galaxies hence are completely off the burst strength – galaxy mass relation for starbursts in non-interacting

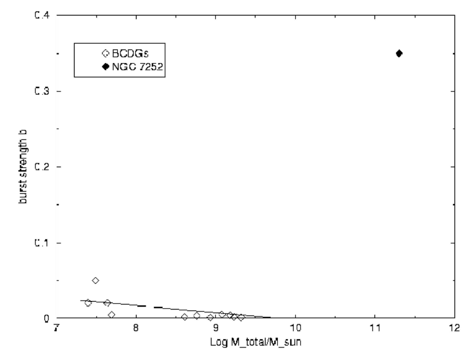

Figure 1: Burst strengths vs. total galaxy mass for the sample of BCDGs from Krüger, Fritze – v. Alvensleben & Loose (1995) and for the post-starburst galaxy NGC 7252, for which the symbol only gives a lower limit (Fritze – v. Alvensleben & Gerhard 1994b).

dwarf galaxies, as seen in Fig. 1, raising the question if the SF process is the same or different in normal SF regimes and dwarf galaxy starbursts on one hand and in violent starbursts triggered by mergers of massive gas-rich galaxies on the other (see also Fritze – v. Alvensleben 1994).

Star **F**ormation **E**fficiencies (**SFE**s), as defined by the amount of stars formed out of a given amount of gas SFE $:= M_{stars}/M_{gas}$ vary tremendously between the two regimes. On a global scale, SFEs are of order $0.1-5$ % for spiral, irregular, and dwarf starburst systems (e.g. Murgia *et al.* 2002), whereas they can reach $10-50$ % and $30-90$ % in global and nuclear starbursts triggered by massive gas-rich mergers like NGC 7252 and ULIRGs, respectively. Analysing the post-starburst in NGC 7252 by means of evolutionary synthesis models GALEV, we could show that for this galaxy even under the most conservative assumptions of two particulraly luminous and particularly gas-rich progenitor spirals, the SFE during the merger-induced starburst must have been very high, i.e. of order SFE ≥ 40 % **on a global scale**, i.e. 1 or 2 orders of magnitude higher than in normal SF mode (Fritze – v. Alvensleben & Gerhard 1994b). SFEs as high as this had only been thought to occur in the early universe.

SFEs ≥ 20 or even 50 % are required for the formation of star clusters that are masive, compact, and strongly bound enough to be able to survive for a Hubble time, i.e. for **G**lobular **C**lusters (**GC**s), as shown in hydrodynamical simulations of star cluster formation (Brown, Burkert & Truran 1995, Elmegreen & Efremov 1997, Li *et al.* 2004). The high SFE found in NGC 7252 and other mergers led to the idea that GCs might form in these events and not exclusively in the early universe (Fritze – v. Alvensleben & Burkert 1995). By about the same time, first HST images showed the rich star cluster systems now routinely found in starbursts and mergers. The radii of these clusters remained ill-determined by that time due to the aberration problems of WFPC1.

While not much is known about molecular cloud **structures** in interacting and merging galaxies, a clear difference does exist in the molecular gas **content** between normal SFing galaxies and ULIRGS. This knowledge is based on the fact that while the CO(1-0) line traces molecular gas at densities $n \geq 100$ cm^{-3}, the HCN(1-0) and CS (1-0) lines trace gas at densities $n \geq 30\,000$ cm^{-3} and $n \geq 100\,000$ cm^{-3}, respectively. Sub-mm observations show that while for normal SFing galaxies only a small fraction ($\sim 0.1-3$ %) of all their (CO) molecular gas is at the high densities of molecular cloud cores, as traced by HCN or CS, i.e. L(HCN)/L(CO) $\sim 0.001-0.03$, this very high density gas accounts for $50-90$ % of all molecular gas in the central regions of ULIRGs, for which L(HCN, CS)/L(CO) ≤ 1. On scales of a few 100 pc, gas at molecular cloud core densities dominates the dynamical mass in ULIRGs. The molecular cloud structure there can in no way resemble that of the Milky Way and normal SFing galaxies with their tiny HCN cores within large CO molecular clouds. Solomon *et al.* (1992) and Gao & Solomon (2004) find a very

tight correlation between SFRs derived from FIR luminosities and molecular cloud core masses derived from HCN luminosities over a range of more than 3 orders of magnitude in SFRs from normal spirals all through ULIRGs. They also show that, albeit with considerable scatter, the ratio between L(FIR) and the mass of gas at molecular cloud core densities is $\sim$ *const*. This can be interpreted in terms of SFRs directly proportional to the mass of gas at very high densities.

The famous Schmidt (1959) law relating the surface densities of SFR and HI by $\Sigma_{\rm SFR} \sim \Sigma^{\rm n}_{\rm HI}$ with n ~ 1 for spirals/irregulars and n ~ 2 for ULIRGs (Kennicutt 1998), that is valid over 5 orders of magnitude in gas surface density and 6 orders of magnitude in SFR density, becomes a universal $\Sigma_{\rm SFR} \sim \Sigma^{\rm n}_{\rm HCN,\ CS}$ with n = 1 for all SF regimes, when expressed in terms of high density molecular gas. Apparently, the gas at molecular cloud **core** densities is transformed into stars with almost 100% efficiency on short timescales, and the efficiencies and timescales for SF are set by the transformation of low density gas traced by CO into high density gas traced by HCN or CS. This is an important issue to consider in hydrodynamical modelling of galaxies and galaxy mergers which then needs to account for a multi-phase ISM and include a careful description of phase transitions, SF and feedback processes.

SF in normal galaxies, spirals and irregulars, is thought to occur through the collapse of molecular clouds, whereby the mass spectrum apparently remains self-similar from molecular clouds through molecular cloud cores all the way to the mass spectrum of open star clusters, all of which are power laws with m $\sim -1.7 \ldots -2$ (Lada & Lada 2003, cf. Elmegreen & Efremov 1997 for a theoretical foundation). In interacting galaxies, the frequency of molecular cloud collisions increases strongly and this will considerably enhance SF. Moreover, molecular clouds get shock-compressed by external pressure (recently verified observationally for the Antennae galaxies by Haas *et al.* 2005), grow denser and more massive, and this process can drive up the SFE very efficiently (Jog & Solomon 1992, Barnes 2004). Jog & Das (1992, 1996) have shown that a relatively small increase in the external ambient pressure to values $3-4$ times the internal pressure within the molecular clouds in the undisturbed galaxy can drive SFEs up to $70-90$ %.

A first attempt to assess the molecular cloud mass spectrum in the nearest ongoing merger NGC 4038/39 by Wilson *et al.* (2003) revealed a power law with m $\sim -1.2 \ldots -1.6$ but remained limited to a mass range above 10^7 M$_\odot$. Resolution of molecular clouds below that and observations of molecular cloud cores have to await ALMA, and the same is true before we can know if the molecular cloud mass spectrum is different or not in massive gas-rich mergers from what it is in non-interacting galaxies. ULIRGs in any case show that, averaged over volumes of $10-300$ pc, the ratio M(HCN)/M(CO) can reach up to $0.3-1$, i.e. that the molecular cloud structure is very different indeed – to the point that it becomes very difficult to imagine much internal structuring at all, if essentially all the molecular gas is at molecular cloud core densities.

3 Star Cluster Formation

The Milky Way, M31, LMC, SMC,... all are forming open clusters with masses $\sim 10^3$ M$_\odot$, low concentration, and a power law cluster mass spectrum. With their short lifetimes $\sim 10^8$ yr, these open clusters will soon dissolve into the field star population. All these galaxies also have Globular Clusters (**GC**s) with high masses $\sim 10^{5.5}$ M$_\odot$, high concentration, a Gaussian GC mass spectrum and lifetimes of order a Hubble time. The LMC features an intriguing gap in star cluster ages with only one cluster in the age range between 4 and 13 Gyr, although field star formation and chemical enrichment proceeded continuously. Star cluster formation seems to only or predominatly have occurred in epochs of enhanced field star formation that can be associated with close passages of the SMC and/or the Milky Way (cf. Rich *et al.* 2001). Similarly, star cluster formation in M51 is found to have been significantly enhanced during the last close encounter with its companion NGC 5196 (Bastian *et al.* 2005). With SFEs in the normal range, the ongoing cluster formation in normal, non-interacting as well as in dwarf starburst galaxies

is expected to produce open clusters rather than GCs. If some locally exceptionally high SFE might produce a GC is an open issue. The fact that no or at most very few intermediate age GCs are known in normal galaxies confirms that this is at best a very rare case.

Larsen (2004) reports the detection of so-called **S**uper **S**tar **C**lusters (**SSC**s) in a number of undisturbed normally SFing face-on spirals. These SSCs are clearly very bright and very young, at least some of them have been shown to be very massive, too (Larsen *et al.* 2004). With masses around 10^{5-6} $M_{\odot}$ and small radii, they resemble young GCs, although GC formation is not expected in these probably normal, i.e. low SFE environments. If they really were young GCs forming in a non-spectacular way during normal SF in undisturbed spirals, however, we might ask: "Where are the descendants of all those SSCs that formed earlier-on, i.e. where are all the intermediate-age GCs in those spirals? Or are we whitnessing a very special epoch in the life of those spirals? And, in which sense is it special?"

3.1 Star Cluster Masses

There are two fundamentally different methods to assess the masses of **Y**oung **S**tar **C**lusters (**YSC**s). Dynamical mass estimates on the basis of central stellar velocity dispersions yield results independent of any assumption about the stellar IMF. Requiring spectroscopy, however, this method is time-consuming and limited to the brightest and nearest systems. Mass segregation will lead to systematically underestimate dynamical masses. It has been shown to not only occur secularly in the course of dynamical evolution, but to some part already to be built in at birth for YSCs in the LMC by de Grijs *et al.* (2002a, b). Spectroscopy of the brightest SSCs in nearby undisturbed face-on spirals embarrassingly indicates masses in the range 10^{5-6} $M_{\odot}$ for those objects with half-light radii similar to those of GCs (Larsen *et al.* 2004).
Photometric mass estimates, on the other hand, use multi-λ photometry in combination with a grid of evolutionary synthesis models like our GALEV models for **S**imple **S**tellar **P**opulations (**SSP**s with all stars of the same age and metallicity) like star clusters and a dedicated SED Analysis Tool to derive ages, metallicities, extinction values, and masses, including their respective 1 σ ranges **for all clusters in the field** (Anders *et al.* 2004a, Anders & Fritze – v. Alvensleben, *these proceedings*). 4 reasonably chosen passbands (e.g. U, B, V or I, and a NIR band) are enough to obtain reasonably precise estimates of all the relevant parameters, including masses. Based on 4-band imaging, these photometric mass estimates are economic and far-reaching, and yield parameters for all clusters in a field in 4 shots. They have to assume a stellar IMF, and the accuracy of the stellar masses derived strongly depends on the precision of the age determination due to the steep time evolution of M/L-ratios in early stages. Being based on photometric magnitudes, the precision of photometric mass estimates strongly depends on well-defined cluster radii and accurate aperture corrections (Anders & Fritze – v. Alvensleben *this volume* and Anders *et al., submitted*).

3.2 YSC Formation

YSC formation is observed in a wide variety of environments. E.g., in addition to the 3 well-known SSCs in the isolated dwarf starburst galaxy NGC 1569, Anders *et al.* (2004b) identified 166 YSCs on HST archival images, more than 1000 YSCs are seen in the ongoing merger between NGC 4038 and 4039, the famous Antennae galaxies (Whitmore & Schweizer 1995, Whitmore *et al.* 1999, Fritze – v. Alvensleben 1998, 1999, Anders *et al., in prep.*). YSCs are seen in many other interacting and/or starburst galaxies. Sometimes they are found all over the main body of an interacting system, as in the Antennae or NGC 7252, sometimes they are confined in or around a starburst nucleus as is the ULIRGs Arp 220 and NGC 6240 (cf. Shioya *et al.* 2001, Pasquali *et al.* 2003). YSCs are also found all along some, but not all, extended tidal features, like e.g. all along the 120 kpc tidal tails of the Tadpole and Mice galaxies shown in Fig. 2

Figure 2: ACS Early Release Observation of the Tadpole (left) and Mice galaxies (right) showing large numbers of young blue star clusters all along their $\sim$ 120 kpc long tidal tails (Credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M.Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA).

(Knierman *et al.* 2003, de Grijs *et al.* 2003a), as well as in group environments like Stephan's quintet (cf. Gallagher *et al.* 2001).

These environments cover all the range from very dense regions within or close to an active starburst nucleus out to expanding low-surface brightness and probably also low physical density regions far from the galaxy centers and we may ask the question whether or not the YSCs in these very different environments are similar – individually or as a population. In the Milky Way and other local galaxies we are used to distinguish between open clusters on the one hand and GCs (**GC**s) on the other, with open clusters being low-mass ($\leq 10^3$ $M_\odot$) clusters with low central concentration, described by Elson, Fall & Freeman (1987) surface brightness profiles, weakly bound, short-lived with lifetimes of order a few 10^8 yr, and, hence, predominantly young. Only very few open clusters in the Milky Way have ages of 1 Gyr and beyond, those reside in peaceful isolation very far from the Galactic Center. GCs, on the other hand, have high masses $\sim 10^{5.5}$ $M_\odot$, high central concentrations, are described by tidally truncated King models in their surface brightness structure, they are strongly bound and, hence, long-lived, have ages of order 13 Gyr. We do not know whether open clusters and GCs are two different types of objects – by nature or by nurture – or whether they rather form two ends of one continuous distribution in terms of mass and/or concentration. Nor do we know whether or not the formation processes leading to open and globular clusters, respectively, are the same or different, if the formation of one of both types preferentially or exclusively occurs in specific environments or if always the full spectrum of clusters from very massive and strongly bound to very losely bound low-mass clusters is formed.

The young open cluster populations in the Milky Way, M31, LMC, SMC, and other nearby non-interacting, peacefully SFing galaxies feature power-law luminosity functions, while the old GC populations in these galaxies show Gaussian type luminosity functions with $\langle M_V \rangle = -7.3$ mag, $\sigma(M_V) = 1.3$ mag and Gaussian type mass functions with $\mathrm{Log}\langle M_{GC}/M_\odot \rangle = 5.3$.

We do not know much yet about open and globular clusters in starbursting and interacting galaxies, in particular because of the difficulty to distinguish between both types in a YSC system. What GCs and a GC system looked like when they were young is another open issue. For the Milky Way GC system it is for sure that what is left today from the original GC system is just the *hardiest survivors of an originally much larger population*, as stated by W. Harris.

The luminosity of the most luminous YSC apparently increases with increasing number of YSCs in more actively starforming galaxies, as predicted in numerical simulations by Kravtsov

& Gnedin (2005). It is not clear yet, if this increase is only what is expected from a purely statistical size of sample effect or if there is a systematic effect on top of that. This kind of study in any case has to look at cluster masses instead of luminosities, e.g. on the basis of 4 passband photometry in the way described above, because of the very rapid fading of YSCs in early stages. Our models have shown that e.g. at half-solar metallicity a YSC fades by 5 mag in V over the first Gyr with 3.3 mag of fading already in the first 10^8 yr due to stellar evolution only (Schulz *et al.* 2002, Anders & Fritze – v. Alvensleben 2003). If a YSC also loses stars (and how many) by already dissolving into the field star population depends on its initial parameters mass, density, and velocity dispersion (cf. Bastian *et al.* 2005, Lamers *et al.* 2005, Takahashi & Portegies Zwart 2000, Spitzer 1987).

3.3 YSC Masses and Mass Functions

The rapid evolution of cluster luminosities in early stages is the reason why luminosity functions of YSC systems need not reflect the shape of their underlying mass functions. If the age spread among the clusters is of the order of the cluster ages, as is the case for YSC systems forming in massive gas-rich spirals with typical burst durations of a few 10^8 yr, the luminosity function may well look like a power-law with the mass function showing a clear turn-over like the Gaussian mass function of old GC systems (Meurer 1995, Fritze – v. Alvensleben 1998, 1999). Already when analysing the WFPC1 data in U, V, and I obtained by Whitmore & Schweizer (1995) for the Antennae, assuming half-solar metallicities and carefully accounting for the individual ages of the 393 YSCs with precise enough color information, we found a Gaussian cluster mass spectrum with $\log\langle M_{YSC}/M_{\odot}\rangle \sim 5.6$ and $\sigma = 0.46$, very similar to the GC mass spectra in the Milky Way, M31, and nearby elliptical galaxies. The major drawback in our analysis was our assumption of a uniform reddening for all YSCs lack of more detailed information about individual clusters. Zhang & Fall (1999) used reddening-free Q-parameters in their analysis of the deeper WFPC2 data and found a power-law mass function. The major drawback in their analysis was that they had to exclude an important fraction of clusters for which the Q-parameters did not yield an unambiguous age. Excluding this age group of clusters in our models also leads to a power-law MF. Hence, by that time, the MF of YSCs forming in this merger-induced starburst remained controversial. A reanalysis of WFPC2 data including H_{α} by Fall (2004) confirmed their earlier result of a power-law MF for the YSCs (age $< 10^8$ yr) in the Antennae. Recently, we have begun to reanalyse the WFPC2 data for the Antennae with our SED Analysis Tool and very conservatively identify $\sim$ 1000 clearly extended YSCs with photometry in UBVI accurate to at least 0.2 mag. We are currently examining very carefully all sources of uncertainties. Among others, we account for different completeness limits for clusters in regions of different background and apply appropriate aperture corrections individually for each cluster. We thus obtain for each cluster its individual metallicity, extinction, age and mass and we will therefore be able to determine with unprecedented significance whether or not the YSC luminosity function will look like a power law as for open clusters in the Milky Way or already show a turn-over like the luminosity function of old GC systems and the luminosity functions of intermediate-age star cluster systems in NGC 1316 (Goudfrooij *et al.* 2004) or the star clusters in the post-starburst region M82-B (de Grijs *et al.* 2003b) (cf. Anders *et al., in prep.*).

3.4 Evolution of Star Cluster Populations

Beyond the evolution of each individual cluster due to stellar evolution and the mass loss it brings along, star clusters also lose mass in terms of stars in the course of their dynamical evolution. Stars are lost from the tail of the Maxwellian stellar velocity dispersion, that, in turn, keeps being replenished due to 2-body relaxation. This effect leads to the evaporation of star

clusters and, of course, destroys low-mass clusters in particular. This evaporation due to 2-body relaxation of stars within the cluster can be enhanced by tidal shocking if a cluster on its orbit sees a variable potential, e.g. by crossing a disk or by passing close to a galaxy center on an excentric orbit. It may then also destroy higher mass clusters on short timescales. These effects are included in semianalytical and numerical dynamical modelling of star cluster populations in Galactic potentials, timescales depend on the mass of a cluster and on its initial concentration (cf. Chernoff & Weinberg 1990, Fall & Zhang 2001). Both the initial cluster mass function and the initial distribution of densities or concentrations are not known for the progenitors of old GCs, nor for YSC systems in interacting and starburst galaxies.
Another process that can only be accounted for in numerical models that consistently include the internal dynamics within clusters evolving in a Galactic potential is dynamical friction affecting predominantly high-mass clusters near the galaxy centers. Both for a Milky Way-type and an elliptical galaxy potential, Vesperini and collaborators find that the destruction of low-mass clusters by evaporation and the destruction of high-mass clusters by dynamical friction largely balance each other and that despite of the destruction of more than 50 % of the original cluster population in the course of evolution an initially Gaussian-shaped cluster mass function is generally preserved while an initially power-law type mass function requires significant fine-tuning of all the parameters involved in the modelling to be transformed into the Gaussian observed for Milky Way GCs (Vesperini & Heggie 1997, Vesperini 2000, 2001, Vesperini & Zepf 2003). All this, however, has only been calculated for static galaxy potentials. In the time-varying potential of an ongoing merger like the Antennae, where violent relaxation, external pressure, violent SF and feedback are vigorously at work, things are definitely more complicated.

Timescales for star cluster destruction processes can also be derived from observations of YSC systems. Under the assumption that YSCs were formed at a continuous rate and with similar properties over the duration of a starburst, comparison of YSC subgroups from several age bins within the typically $2 - 4 \cdot 10^8$ yr duration of starbursts in massive gas-rich mergers, can show what fraction of clusters still seen in the youngest bin is already missing from the older bins. This way, timescales for the fastest cluster destruction processes can be estimated empirically and are found to be in broad agreement with theoretical estimates (cf. Boutloukos & Lamers 2003, Lamers *et al.* 2005). If the assumptions of a constant YSC formation rate during the burst and of uniform YSC properties are correct or not is crucial for this approach and remains to be tested by detailed observations of YSC systems and subpopulations in various environments.

In any case, it is crucial to account for destruction effects when comparing star cluster (sub-) systems of various ages and deriving initial cluster mass functions. At present, it remains to be seen if and in how far initial mass functions of YSC systems are universal or dependent on environment and if they resemble initial GC mass functions or not. As long as we cannot resolve molecular clouds and molecular cloud cores in interacting systems and determine their mass spectra, the initial mass function of the YSCs forming in these systems has to serve us as a proxy and is the only way to check in how far the SF process is the same or not in the strong merger-induced starbursts and in normal SF regimes.

The masses of the YSCs in the Antennae range from a few 100 $M_\odot$ for the smallest OB association-like clusters through $\geq 10^6$ $M_\odot$ (Mengel *et al.* 2002), i.e. definitely into the range of GC masses. Their radii, as determined by Whitmore *et al.* (1999), are within the range of Milky Way GC radii, a more careful redetermination by P. Anders is under way, as well as correspondingly improved photometry, photometric masses, and their mass function.

NGC 1569, on the other hand, is an isolated dwarf galaxy with a strong starburst going on. Three so-called Super Star Clusters and some 44 YSCs were previously known (Hunter *et al.* 2000). On HST archival images provided to us by an ESO ASTROVIRTEL project (PI R.

de Grijs) Anders *et al.* (2004b) identified 169 YSCs in total with accurate photometry in U, B, V, I, and H (errors < 0.2 mag), for which by means of our SED Analysis Tool individual metallicities, ages, extinction values, and masses including their respective 1σ errors could be determined. The YSCs in this system turn out to have masses in the range $10^3 - 10^4$ $M_\odot$, only three clusters have masses beyond a few 10^5 $M_\odot$, the average mass of old GCs. Hence, we conclude from the masses alone that no or, at most, very few young GCs are formed in this non-interacting dwarf starburst galaxy.

3.5 The Fate of Young Star Clusters in Mergers

From the example of NGC 7252, where a large number of star clusters that formed in the burst between 650 and 900 Myr ago are still alive and compact, we know that GCs indeed did form in this massive gas-rich spiral – spiral merger, since those clusters have already survived many crossing times. In this respect, NGC 7252, one of the most widely (from X-rays through radio) observed merger remnants, for which we had found the very high SFE in the first place, holds a key role in that it really shows that a number of clusters with GC masses and radii do still exist at ages where most open clusters already were destroyed, and in a number comparable to the number of GCs typically inherited from the two spirals. What we do not know, on the other hand, is how many YSCs were formed in total in NGC 7252, i.e. what fraction of the originally formed entire YSC population did survive and hence, merit to be called young GCs.

We are unable to tell apart the YSC populations in the Antennae or NGC 1569 individually into young open clusters and young GCs. As we have shown before, neither their luminosities nor their radii fall into two distinct categories. At their ages, these YSCs are not expected to be tidally truncated yet by their parent galaxy potential and Whitmore *et al.* (1999) show that the YSCs #405 and #430 in the Antennae show HST determined surface brightness profiles without indication of a tidal truncation, similar to the young (8 – 300 Myr) clusters in the LMC (Elson, Fall & Freeman 1987). Hence, the classical measure of concentration parameters $c := \log(R_{tidal}/R_{core})$ cannot be applied.

We are trying hard (Anders *et al., in prep.*) to see any difference or gap in YSC properties in the Antennae in terms of masses, half-light radii, or densities after our very careful radius determinations. Very preliminary results fail to indicate any significant differences, neither within the entire population nor between different age groups, in agreement with Elmegreen & Efremov's (1997) theoretical scenario. They suggest that supersonic turbulence produces a scale-free fractal structure in the gas and a universal $m \sim -2$ power-law mass spectrum for the clouds and for the forming clusters. Cloud mass and ambient pressure determine the degree of internal binding in the nascent cluster and, hence, if the result is either unbound, or a weakly bound open cluster, or a strongly bound GC. In their scenario, by raising the ambient pressure, galaxy interactions can lead to a mode of SF in which massive, dense, and tightly bound clusters are the **primary** result, although to some degree the entire continuum down to losely bound/unbound clusters should also be present.

We know both from dynamical modelling and from evolutionary synthesis that spiral – spiral mergers can well evolve into E/S0 (and in some cases even Sa) galaxies morphologically and spectroscopically (e.g. Barnes & Hernquist 1992, Bournaud, Combes & Jog 2004, Springel & Hernquist 2005, Fritze – v. Alvensleben & Gerhard 1994a). The spectroscopic type of the merger remnant depends on whether or not the SFR after the merger-induced starburst goes to zero or remains at some finite value. Here again, NGC 7252 holds a key role: Hibbard *et al.* (1994) have observed the amount and kinematics of HI along its tidal tails and find that there is a considerable reservoir of HI falling back onto the body of the merger remnant on long timescales of order 3 – 4 Gyr. In simulations by Hibbard & Mihos (1995) this gas is seen to settle into a radially growing HI disk. We predict a comparable amount of gas to be released by

dying burst stars (Fritze – v. Alvensleben & Gerhard 1994b). All this gas can be transformed into a stellar disk if the present SFR of 1.5 – 3 $M_\odot$ yr^{-1} would continue in NGC 7252.

We hence expect that those ellipticals, S0s (and Sa's), that are remnants from massive gas-rich mergers should feature a younger and more metal-rich subpopulation among their GCs with the age of this subpopulation dating back to when the merger occured and the metallicity being roughly set by the ISM abundance in the merging spirals. I put "roughly" because of metallicity gradients within the spirals, differences between various spiral types, and the possibility that clusters formed late in the burst could already be burst-enriched, an effect that would reveal itself by an α-enhancement in the cluster spectra, as tentatively seen in the spectrum of the YSC W3 in NGC 7252 (Schweizer & Seitzer 1993 and Fritze – v. Alvensleben & Burkert 1995).

In Fritze – v. Alvensleben (2004) I have used GALEV models for the chemical evolution of various spiral types to show that despite considerable scatter a broad age – metallicity relation exists for spiral galaxies, analogous to the one for stars in the Milky Way. The later the merger occurs, the higher will be the metallicity of the star clusters expected to form.

Zepf & Ashman (1993) found that the specific GC frequency, i.e. the number of GCs per unit galaxy mass, is typically twice as high in E/S0s as in spirals and they predicted that an average elliptical can only result from a merger of two average spirals if a number of GCs can form in the burst that is of the order of the number of GCs present in the two spirals before they merge. This has indeed been the case in NGC 7252, as we showed in Fritze – v. Alvensleben & Burkert (1995).

A number of intermediate age GC systems have been reported in merger remnants and dynamically young ellipticals (e.g. Goudfrooij *et al.* 2001a, b). And many, if not most, bright ellipticals and S0s do feature bimodal color distributions for their GC systems in terms of $V - I$ (Gebhard & Kissler-Patig 1999, Kundu & Whitmore 2001a, b). The blue peak seems to be fairly universal and similar to that of the Milky Way halo GC population, the position and relative height of the red GC color peak is variable. The interpretation of these bimodal GC color distributions, however, is not straightforeward due to the well-known fact that optical colors are degenerate in terms of metallicity and age. A young and metal-rich stellar population can have the same color as an older and metal-poor stellar population (e.g. Worthey 1994). While the merger scenario predicts two GC subpopulations, a hierarchical formation scenario would be expected to produce a broad or multi-peaked GC color distribution. Other scenarios for the *in situ* formation of a second GC subpopulation have also been proposed (e.g. Forbes & Forte 2001). In Fritze – v. Alvensleben (2004) I have shown with help of our GALEV models for the spectrophotometric evolution of star clusters, how – depending on its initial metallicity – the color distribution of a secondary GC population evolves with time. A low metallicity cluster population with [Fe/H]$= -1.7$ similar to the Milky Way halo GCs would have its $\langle \mathrm{V-I} \rangle$ at ~ 0.6 at an age of 300 Myr and move towards the universal blue $\langle \mathrm{V-I} \rangle$ peak around 0.9 by an age of 12 Gyr. If a star cluster population starts out with a metallicity around [Fe/H]~ -0.4, it would attain $\langle \mathrm{V-I} \rangle \sim 1.2$ around 12 Gyr, similar to the red-peak GCs in several E/S0s. Because of the age – metallicity degeneracy a red peak at $\langle \mathrm{V-I} \rangle \sim 1.2$ can in principle result from a manifold of very different combinations of age and metallicity, ranging from very young and very metal-rich (2 Gyr, [Fe/H]$= +0.4$) all through very old and metal-poor (15 Gyr, [Fe/H]$= -1.7$). Individual GC spectroscopy is feasible with 10m class telescopes out to distances of ~ 20 Mpc and allows to disentangle ages and metallicities by measuring Lick indices. It will, however, remain very time-consuming and restricted to the brightest GCs in these distant galaxies. HST imaging will be required in order to secure that spectra indeed refer to individual clusters, not to blends. T. Lilly is currently developing an Analysis Tool for Lick spectral indices in terms of ages and metallicities including their 1σ uncertainties in analogy to the SED Analysis Tool developed by P. Anders (Lilly & Fritze – v. Alvensleben 2005a *submitted*, 2005b *in prep.*). Multi-band imaging will, however, remain the most powerful tool for the analysis of significant fractions of GC

populations in external galaxies and I could also show that already the inclusion of photometry in one additional NIR passband can to a fairly large extent resolve the age – metallicity degeneracy. E.g. will the two GC systems mentioned above with different age – metallicity combinations yielding the same $\langle \mathrm{V-I} \rangle \sim 1.2$ show well distinguishable $\mathrm{V-K}$ colors: $\langle \mathrm{V-K} \rangle = 3.5$ for (2 Gyr, [Fe/H]= +0.4) and $\langle \mathrm{V-K} \rangle = 2.3$ for (15 Gyr, [Fe/H]= −1.7).

4 Star Cluster Formation and Star Formation

Star cluster formation clearly is an important mode of SF in starbursts. Meurer *et al.* (1995) already pointed out that ~ 20 % of the UV-light in starbursts is from star clusters, they tentatively conclude from a sample of starburst galaxies that the UV-light contribution from clusters relative to the total UV-light seems to increase with intrinsic UV surface brightness of the galaxy. Elmegreen & Efremov (1997) and Kravtsov & Gnedin (2005) expect from numerical simulations that the fraction of SF that goes into star cluster formation and into massive, dense, and tightly bound young GCs in particular, should increase in high external pressure and, hence, high SF environments.

In our pixel-by-pixel analysis of the HST ACS Early Release Observations of the Tadpole and Mice galaxies we found large numbers of YSCs with characteristic masses of $\sim 3 \times 10^6 \mathrm{M}_\odot$ all along the tremendous 120 kpc long tail of the Tadpole and along the prominent tail of one of the Mice galaxies and we estimated their light contribution to amount to ~ 70 % in the B-band and to ~ 40 % in I (de Grijs *et al.* 2003a). We concluded that both in the Mice and the Tadpole galaxies more than 35 % of all SF along the extended tidal structures went into star cluster formation, even into the formation of massive clusters with characteristic masses in the range of GC masses. In view of the expanding nature and presumably low physical density of the low surface brightness tails this appears surprising. SCs are very young, $(1.5-2) \cdot 10^8$ yr, profiles and radii are hard to come by (diameters ≤ 35 pc), so it is difficult to estimate for how long these YSCs are expected to survive.

5 Summary, Open Questions, and Outlook

Stars and SCs form from molecular clouds with the timescale and efficiency of SF being set by the transformation of lower density molecular gas, as traced by CO, into high density gas as traced by HCN- and CS-lines. Shocks and external pressure as occuring in galaxy mergers can greatly enhance this transformation, increase the SF efficiency by up to two orders of magnitude, and possibly the ratio of SF that goes into SC formation as well as the degree of internal binding of the emergent clusters. We have no information yet about the molecular cloud structure in the high pressre environments caused by mergers but we know from integrated CO-, HCN-, and CS-luminosities that in ULIRGs, all of which are advanced stages of massive gas-rich mergers, essentially all of the molecular gas $(50-100$ %) is at the very high densities typical for molecular cloud cores. It seems difficult to envisage much structuring within this gas.

With ALMA, it will be of prime interest to compare the molecular cloud structure and mass spectra in interacting galaxies with those of galaxies undergoing normal SF to check whether or not the SF process itself is universal with a tremendous dynamical range or whether there are intrinsic differences between normal and violent SF modes. As long as we cannot yet resolve molecular clouds and cloud cores in interacting galaxies, the YSCs forming in these systems will have to serve as a proxy.

It is clear that star cluster formation is an important mode of SF – already in the Magellanic Clouds, in actively SFing undisturbed spirals with SSCs, and, in particular, in the strong starbursts triggered by interactions and merging between gas-rich galaxies.

Not yet clear on the other hand is whether the relative amount of SF that goes into star cluster formation increases with increasing SFR, burst strength b, SFE, etc., as expected from theoretical models.

It is clear that the formation of strongly bound and hence long-lived star clusters like GCs requires exceptionally high SFEs that apparently were ubiquitous in the early universe and are still achieved occasionally on galaxy-wide scales in violent gas-rich mergers like NGC 7252 that did form systems of new GCs comparable in richness to the preexisting ones.

Not clear is whether there is a threshold in SFR, b, or SFE, below which GCs cannot be formed at all or if SFEs high enough for GC formation can in some cases be reached very locally within an undisturbed spiral, giving birth to just one or few GCs. A careful analysis of spiral galaxy GC populations with respect to possible outlyers in terms of age and metallicity should tell. This analysis, however, gets complicated by the fact that such younger and more metal-rich GCs will not stand out in optical broad-band colors due to the age – metallicity degeneracy.

It is not clear yet if the maximum star cluster mass scales with SFR, b, SFE, and/or total number of YSCs. It is not clear either if in strong merger-induced starbursts like the Antennae or NGC 7252 the usual weakly bound open clusters and associations also form and to what extent. I.e., it is not clear if YSCs are the same or different – individually or as a population – in different environments like isolated and interacting, dwarf and giant galaxies, within their central parts and far out along expanding tidal structures. The starburst in the isolated dwarf galaxy NGC 1569 apparently did not form any GCs, or at maximum very few, as deduced alone from the masses of its numerous and bright YSCs. Gas-rich dwarf – dwarf galaxy mergers, if they weren't so hard to find, seem to be a very interesting case to test if they can reach the very high SFE regimes, if it is the short dynamical timescales, the shallow potentials of dwarf galaxies or the lack of ambient pressure that accounts for the low SFEs in the isolated dwarf starbursts studied so far.

We still are unable to tell which and how many of the YSCs are open clusters and which and how many are young GCs. Their masses, radii, and mass function seem to be the key issues. Comparison of subpopulations of various ages in mergers/starbursts going on for a while may hold clues, provided SC destruction effects are taken into account. A comparison between the relative amounts of SF that go into fields stars and short-lived clusters on the one hand and into strongly bound and long-lived clusters on the other over a wide range of bursts strengths, SFEs and environments (non-interacting vs. mergers, gas-rich vs. gas-poor, giant vs. dwarf) would greatly enhance our understanding of global SF in galaxies.

Long-lived star clusters, in any case, are valuable tracers of the (violent) SF histories of their parent galaxies – much better suited than integrated light, because they can be analysed one-by-one, are easy to interprete (one age, one metallicity), and the age and metallicity distributions of star cluster systems give direct insights into their parent galaxies' formation and chemical enrichment history. Accurate 4-passband photometry over a long enough wavelength basis, including U (or at least B) and one NIR band, in combination with a dedicated analysis tool can largely disentangle the age – metallicity degeneracy and allows to simultaneously determine individual ages, metallicities, extinction values, and masses including their respective 1σ uncertainties for large cluster samples. Resolution of the clusters and accurate cluster radii are the critical issues.

Star clusters are of threefold importance: they are uniquely suited to study the very SF and SC formation processes and their universality vs. environmental dependence, to study their parent galaxy's formation, evolution and chemical enrichment histories, and, as long as we cannot even resolve molecular clouds and cloud cores in the nearest interacting galaxies, the youngest SC systems have to serve as a proxy for the molecular cloud structures they were born from.

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